Carderock Division
Naval Surface Warfare Center
West Bethesda, MD 20817-5700

NSWCCD-65-TR–2001/23 October 2001

Survivability, Structures And Materials Directorate

Technical Report

Structural Integrity and Damage Evaluation Routine (SIDER) for Quality Control and Health Monitoring of Structures

by

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DEPARTMENT OF THE NAVY

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Subj: COLLABORATIVE STRUCTURAL EVALUATION OF A HIGHWAY COMPOSITE DECK BRIDGE

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1. Reference (a) requested the Naval Surface Warfare Center, Carderock Division (NSWCCD) to perform an investigation into using broadband vibration data to monitor the structural integrity and health of an all-composite road bridge. Enclosure (1) presents a broadband vibration-based Structural Integrity and Damage Evaluation Routine (SIDER) which has been shown to be sensitive and repeatable when used on civil infrastructure such as road bridges.

2. Comments or questions may be referred to Dr. Roger M. Crane, Code 6553; telephone (301) 227-5126; e-mail, CraneRM@nswccd.navy.mil.

J. E. BEACH
By direction

Subj: COLLABORATIVE STRUCTURAL EVALUATION OF A HIGHWAY COMPOSITE DECK BRIDGE

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Enclosure (1)

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14. ABSTRACT
This report presents a broadband vibration-based Structural Integrity and Damage Evaluation Routine (SIDER) which has been shown to be sensitive and repeatable when used on civil infrastructure such as road bridges. The routine looks for features in complex curvature operating shapes, and was developed to assist in the inspection of deep-section FRP structures that cannot be inspected using more conventional methods. The report presents a theoretical outline of the procedure and an experimental demonstration using impacted foam core composite panels. The report also presents the results of a three-year effort inspecting an all-FRP road bridge in Glasgow, Delaware. It is shown that the routine can locate small amounts of incipient damage and can monitor the propagation of this damage.

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composite structures, structural assessment, non-destructive testing

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Administrative Information

The work described in this report was performed by the Structures and Composites Department of the Survivability, Structures, and Materials Directorate, at the Naval Surface Warfare Center, Carderock Division (NSWCCD), in conjunction with the United States Naval Academy and the University of Delaware. The work was funded by the Office of Naval Research, Code 332, under the Seaborne Structures Materials Program (PE 0602234N) under the guidance of Mr. James J. Kelly.

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Introduction

In order for bridges to remain in operation, they are routinely inspected by various state and federal agencies. In many cases, the primary procedure is a visual inspection for rust, spalled concrete and general degradation. In recent years there has been an increasing interest in manufacturing bridges using fiber-reinforced plastic (FRP) composite materials. These structures can have cores up to 30 inches thick, and neither visual inspection nor conventional methods used to inspect FRP structures can determine the integrity of these cores. In order to verify the structural integrity of such structures, new inspection methods are required.

This report presents a vibration-based method that has been shown to be sensitive and repeatable. The concept of using vibration methods to identify damage in structures is not new. Resonant methods based on modal data have been used both to identify that damage exists, and to locate it. Some techniques, such as those by Kashangaki (1995), Hajela and Soeiro (1990), Crema et al (1995), Cawley and Adams (1979a), Manning (1994), Liu (1995), Chen and Garba (1988), Li and Smith (1995), Adams et al (1991), and Lim and Kashangaki (1994), treat framework structures as discrete systems, and compare the modal behavior of the damaged structure with that of the undamaged structure. For continuous systems such as beams and bridges, damage detection often focuses on the changes in natural frequencies and/or mode shapes which occur when the structure is damaged, as presented by Cawley and Adams (1979b), Okafor et al (1995), Peroni et al (1991), Vantomme (1992), Miller et al (1992), Casas and Aparicio (1994), Liang et al (1997), and Chang et al (1993). However, usually only relatively severe damage will cause a sufficiently large change in the displacement mode such that damage can be located. Therefore, using a displacement mode shape by itself to locate damage may not be reliable (Yuen, 1995). Some authors, including Pandey et al (1991), Ratcliffe (1997) and Maia et al (1997) have found that strain or curvature mode shapes (surface strain in a beam is proportional to curvature) are more effective at locating damage.

The original concept for the work reported here is a study by Ratcliffe and Bagaria (1998) who developed a resonant method which could locate damage such as a delamination in a composite beam. This work was extended to broadband by Ratcliffe (2000). This extension eliminated the requirement for a modal inferposition of the experimental data, and also showed a significant increase in sensitivity. The work at that time was limited to one-dimensional components such as beams.

In this report, the work is extended for two-dimensional components, and is also modified to improve its suitability for real-engineering applications. The report presents a theoretical outline of the procedure and an experimental verification which has been used to locate damage in control impacted composite panels. The report also presents the results of a three-year effort inspecting an all-composite road bridge in service in Glasgow, Delaware, where it is shown that the test procedure can monitor both global and local changes in structural integrity during the service life of the bridge.

Summary of the One-Dimensional Broadband Gapped-Smoothing Method (BGSM)

The method presented here is developed from Ratcliffe's (2000) one-dimensional Broadband Gapped-Smoothing Method (BGSM). The BGSM operates on frequency-dependent complex operating deflection shapes (ODS) which are obtained from a set of frequency response functions (FRFs) measured for a set of test points equally spaced along the length of the structure. Typically, these FRFs are obtained using a digital spectrum analyzer and thus contain data at discrete frequencies. Each frequency-dependant ODS is extracted as the values of the FRFs at that frequency. Once the ODS for each analysis frequency has been determined, it is spatially differentiated to convert it to an operating curvature shape (OCS) using the finite difference approximation of Equation (1). Equation (1) is applied separately to the real and imaginary parts of the ODS.

$$C_i = (y_{i+1} + y_{i-1} - 2\, y_i) \,/\, h^2 \tag{1}$$

In Equation (1), y_i is the value of the ODS at the i-th spatial position on the structure, and h is the spatial separation between test points. C_i is the resulting value of the OCS for the i-th spatial position. Note that when the measured FRFs are acceleration-based, as is often the case for experimental work, the acceleration measurements do not have to be converted to displacement for the BGSM.

As reported by several authors, including Ratcliffe (1997, 2000), the OCS has a characteristic feature near a point of structural stiffness irregularity. In order to extract this feature from the OCS, while also offering a degree of smoothing for experimental data, the BGSM first fits a gapped cubic polynomial to the OCS function, with separate functions being fitted to the real and imaginary part of the complex function. As an example, when the cubic calculated for the i-th element of the curvature, C_i, at position x_i along the beam, is defined by the formula

$$p_0 + p_1 x_i + p_2 x_i^2 + p_3 x_i^3 \tag{2}$$

the polynomial coefficients p_0, p_1, p_2 and p_3 are determined from curvature elements C_{i-2}, C_{i-1}, C_{i+1} and C_{i+2}. Curvature element C_i is gapped from (left out of) the curve fitting calculation. Separate cubic polynomials are determined for the real and imaginary parts of the OCS.

The damage index, $\delta_{f,i}$, for the f-th frequency and the i-th grid point is calculated as the difference between the experimental curvature and the values of the cubic polynomials calculated at that position as follows:

$$\delta_{f,i} = \left(p_0 + p_1 x_i + p_2 x_i^2 + p_3 x_i^3 - C_i \right)^2_{f,\,REAL} + \left(p_0 + p_1 x_i + p_2 x_i^2 + p_3 x_i^3 - C_i \right)^2_{f,\,IMAGINARY} \tag{3}$$

The procedure is repeated separately for every frequency and for every test point on the structure. For a one-dimensional structure (beam), the resulting output can be shown as a contour plot of frequency versus position. Figure 1 shows the results of an experimental BGSM for a 0.914 m long × 76.2 mm wide × 6.33 mm thick steel beam with simulated damage created by milling a 0.13-mm deep groove across its width. The resulting damage index plot has a feature which shows consistently at nearly all frequencies at the location of damage (grid point 12.5). It should be noted that one advantage of using the BGSM is that it does not require a footprint of information about a presumably undamaged structure (either finite element or experimental). This means that the BGSM is suited to the inspection of structures that have been in service for some period without a prior inspection.

The Quasi Two-Dimensional Structural Integrity and Damage Evaluation Routine (SIDER)

While the one-dimensional method is acceptable for a structure where a single line of test points is sufficient, it is not appropriate when a two-dimensional mesh of grid points is necessary as, for example, for such components as bridge decks. A direct conversion of the BGSM to two dimensions requires a two-dimensional OCS using a two-dimensional variant of the finite difference equation (1) and modification to the gapped-smoothing procedure to consider two-dimensional curvature. These modifications are feasible, however it transpires that a procedure that provides a more sensitive result is to divide the structure into a series of intersecting straight lines and to apply the one-dimensional BGSM to these lines.

Consider, as an example, a rectangular mesh of intersecting lines on a large composite structure which consists of lines with a north-south and east-west orientation. The points of interest will be those created by the intersection of these lines. The first step in the two-dimensional analysis is to run the one-dimensional BGSM separately for each north-south line of test points. The procedure is then repeated separately for each east-west line of points. The entire procedure is also repeated for each measurement reference accelerometer and each frequency. It is assumed here that the test procedure is impact excitation referenced to several fixed accelerometers. However, this restriction is not a fundamental requirement of SIDER. Any test method that generates FRF data between an array of measurement points and several fixed points is acceptable.

As described, for each test point in the mesh a separate damage index is calculated for:

a. the east-west line of points created by the intersecting lines of the rectangular mesh,

b. the north-south line of points created by the intersecting lines of the rectangular mesh,

c. each frequency in the FRFs, and

d. each reference accelerometer.

For FRFs with 1601 spectral lines, the procedure will calculate (1601 spectral lines) × (2 N-S, E-W lines) = 3,202 separate damage indices for each test point and each accelerometer.

Experimental Demonstration – Impacted Foam Core Panels

The procedure was used to locate known defects in composite panels. Several 0.9 x 1.2 m (3 ft by 4 ft) foam core panels were manufactured. The cores were one-inch thick low density HY80 PVC foam (5pcf). The face sheets were 3 mm (1/8 inch) thick E-glass woven roving infiltrated with Dow Derakane 510A vinyl ester resin. The panels were then impacted with varying amounts of impact energy, after which the SIDER procedure was used to locate the damage. For the vibration examinations four reference accelerometers were used and the mesh typically consisted of 27 lines × 24 lines, giving 648 test points and requiring about four million damage index calculations.

The difficulty is how to visualize such a large data set. Various methods have been tried, including watching animations of the damage index as a function of frequency. While watching animations can be informative, it is difficult to get a repeatable interpretation which can easily be archived. A simple and effective alternative method of presenting the data is to look at each point on the structure, and average all the damage indices calculated for that point. Hence, for the mesh of 648 test points, the four million separate damage indices are reduced to a single matrix of 648 numbers. This reduced data set is then presented on a single contour summary plot.

Figure 2 shows the reduced summary plot for one of the foam core panels that was impacted at its center with a 4-inch diameter spherical tup at an energy level of 1344 ft-lbs. The SIDER procedure indicates that, in addition to the damage at the impact site, there is other damage approximately along the diagonals of the panel. After this vibration examination was complete the panel was end-loaded to destruction. The panel failed along the lines identified by the SIDER analysis.

In comparison, Figure 3 shows the SIDER summary plot for a panel that had not been impacted. The plot does not show any features of significance, suggesting uniformity and a lack of damage.

Statistical Enhancement of the Summary Index Plots

The summary index plots tend to be very busy and are not always easy to interpret. One of the reasons for this is that experimental data are not perfect. Despite the smoothing built in to the detection algorithm, areas of the structure that are otherwise uniform will show low levels of damage index. When shown on a summary contour plot, the eye can be distracted by areas of insignificant, but visually attracting, low-level activity. Therefore, the next step toward developing an engineering-friendly tool is to apply a statistical enhancement to extract the features of significance.

The postulate is that the SIDER raw summary predominantly includes insignificant damage indices generated by noise and minor structural variations. The summary also includes some areas that are of interest and are statistically significant. The aim of the enhancement is therefore to determine which values are at some statistical level of confidence above the noise threshold. The statistical enhancement is conducted in the following steps:

It is assumed that the "noise" indices are normally distributed, and the significant indices are "outliers" from this distribution. There are several standard methods of identifying the outliers. The procedure used here is the Thompson's-τ method as recommended by ANSI/ASME (1986). The "noise" mean and standard deviation are calculated for the summary data after removal of outliers. For the complete summary data set (i.e., with the outliers reinstated) all values are then converted to standard deviation normalized values as:

$$(\text{normalized value}) = \frac{(\text{value - noise mean})}{(\text{noise Standard Deviation})} \tag{4}$$

All values in the standardized summary plot that fall below a selected level of confidence are arbitrarily set to zero since these values are not statistically significant and are to be ignored. For the results presented here, a confidence level of 95% was chosen, thus all normalized values less than 1.96 were zeroed out. The value 1.96 is taken from the cumulative normal distribution function for a data set with more than 30 values. A different limiting value would be required for a different level of confidence.

Figures 4 and 5 show the same information as Figures 2 and 3, but after statistical enhancement. The damage on the impacted panel is much easier to interpret, and the plot for the undamaged panel is much 'cleaner'.

Full-Scale Demonstration – Delaware Bridge 1-351

Delaware Bridge 1-351 is located on Business Route 896 in Glasgow, Delaware. Figure 6 shows the bridge during installation, shortly before it was opened to traffic in November 1998. The bridge consists of two E-Glass/vinyl ester sections each 3.9 m (13-ft) × 10 m (33 ft) joined in the traffic direction. The section is a sandwich construction consisting of a 0.7 m (28-inch) deep core and 0.013 m (0.5-inch) thick face sheets covered with approximately 0.038 m (1.5-inch) of latex modified concrete. During installation, the two sections were bonded together and were held in alignment with a composite splice plate, which is now covered with the concrete wear surface.

A vibration examination of this bridge has been conducted annually from 1999 to 2001. For the vibration examinations, four reference accelerometers were used and the mesh on the top surface of the deck consisted of 21 lines × 26 lines, giving 546 test points in all. For additional research purposes, the bottom surface of the deck was also tested, bringing the total number of test points to 1050. Data capture for this entire effort took less than six hours each year. The SIDER for the top surface required about seven million damage index calculations. While this may seem excessive, an optimized program written in Visual BASIC running on a 400 MHz

laptop completed the SIDER analysis in a little under 20 minutes, much less time than it took to drive back from the bridge to the office.

The summary plot for the 2001 examination is shown in Figure 7, and Figure 8 shows the statistically enhanced plot. These figures show the center north-south splice plate (as a horizontal feature). The ability to locate this structural feature is quite significant since the mode shapes from a detailed modal inferposition of the bridge deck did not indicate any anomalous features that would be indicative of this splice plate. The figures also show features at the north and south edges. These features are coincident with known manufacturing or installation irregularities on the bridge.

While not shown here, the summary plots for 1999 and 2000 were very similar to the 2001 plots, showing the SIDER procedure is repeatable.

Long-Term Monitoring

The speculation is that known structural anomalies will appear at every inspection and they will not degrade the performance of a bridge unless they propagate or change. The summary plots can be compared to identify whether there is any such propagation. Summary plots can be determined by annual (or other period) inspections, and the rate of change of damage index over time can be determined. The rate can be calculated by a simple linear regression but it is probably better to apply a weighted regression, with increased importance being attached to the most recent inspection results.

The resulting "rate" information is a raw contour plot. This looks similar to the raw contour plots from a single SIDER analysis, except that the new plot shows the rate of propagation of structural irregularity. Similar to the statistical enhancement used for the individual SIDER plots, the rate plot is also best observed after statistical enhancement. As an example, Figure 9 shows the rate plot for the Delaware bridge, determined after three annual inspections. The main feature is on the south edge, toward the east side. This feature is coincident with surface cracking in the concrete wear surface that was repaired by Delaware Department of Transportation between the 2000 and 2001 inspections.

Conclusions

A Structural Irregularity and Damage Evaluation Routine (SIDER) has been described. The routine looks for unusual features in the frequency-dependant curvature operating shapes that can experimentally be measured for existing structures. The report develops a one-dimensional procedure into a two-dimensional functional tool that can be used for existing structures.

The results from the routine include raw irregularity index plots, and plots which are statistically enhanced to show features which have engineering significance. In addition to single-component structural verification, the routine is also suitable for assessing manufacturing repeatability and monitoring long-term changes in civil infrastructure.

Examples included in the report are a three-year study of an all-FRP road bridge in Glasgow, Delaware, and manufacturing checks of FRP bridge deck sections prior to their installation. In all cases, the routine described in the report successfully located structural features which were not observable by traditional inspection methods.

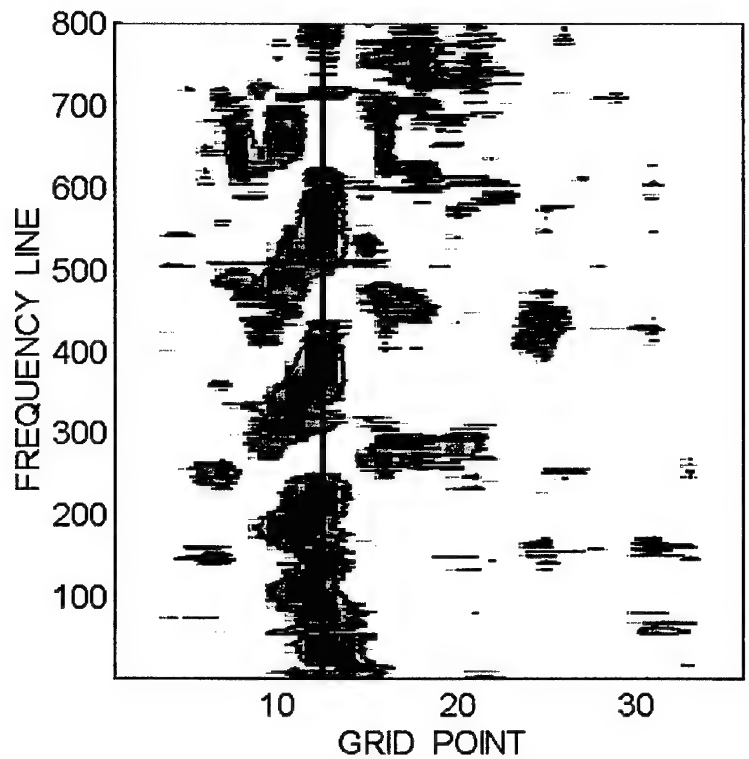

Figure 1. Experimental Broadband Damage Index for a 6.33-mm Thick Steel Beam with a 2.8-mm wide, 0.13-mm Deep Groove at the Position Marked

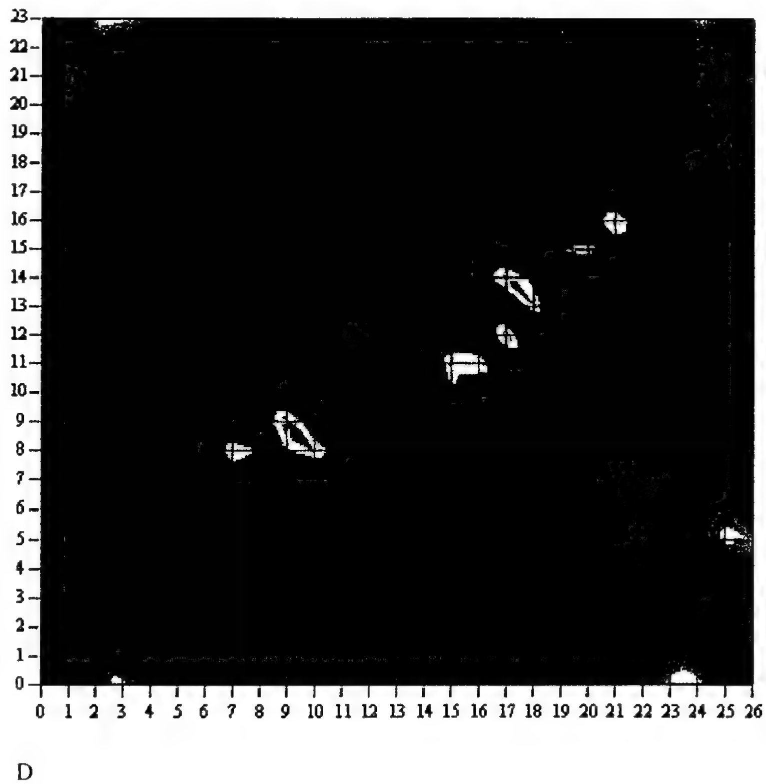

Figure 2. SIDER Summary Plot for Foam Panel after Impact at 1344 ft-lbs

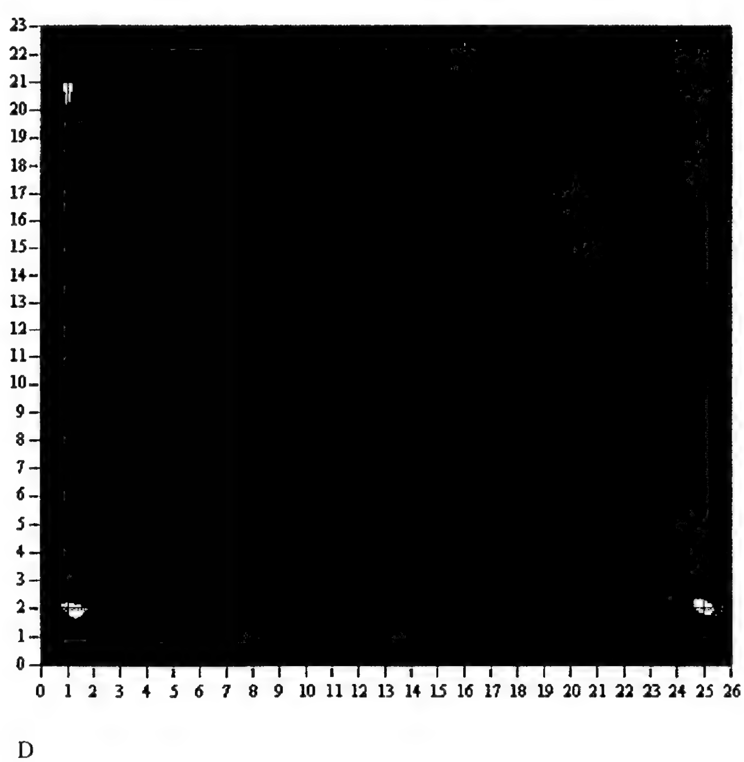

Figure 3. SIDER Summary Plot for Foam Panel that was not Impacted

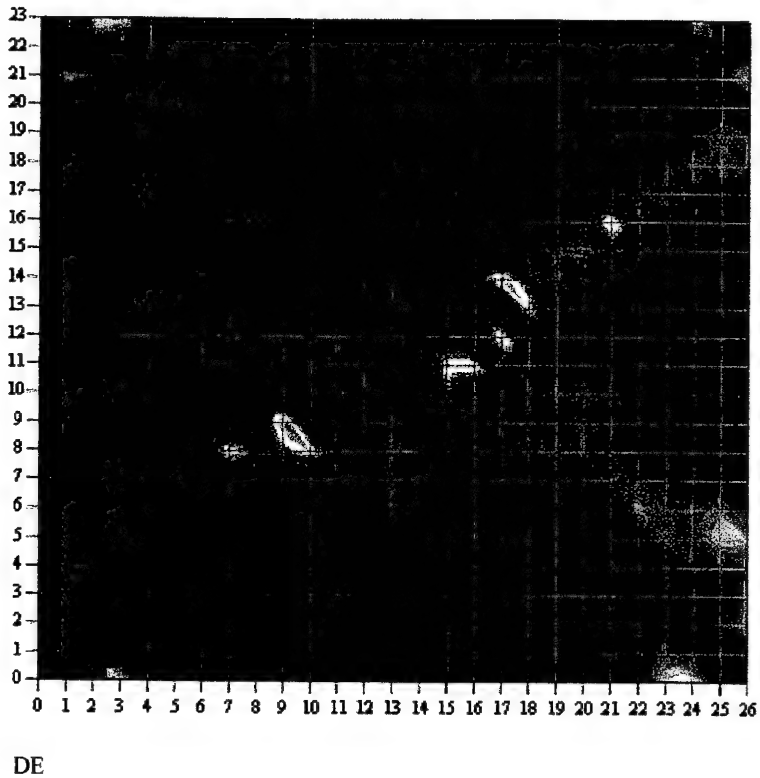

Figure 4. Enhanced Plot for Damaged Foam Panel

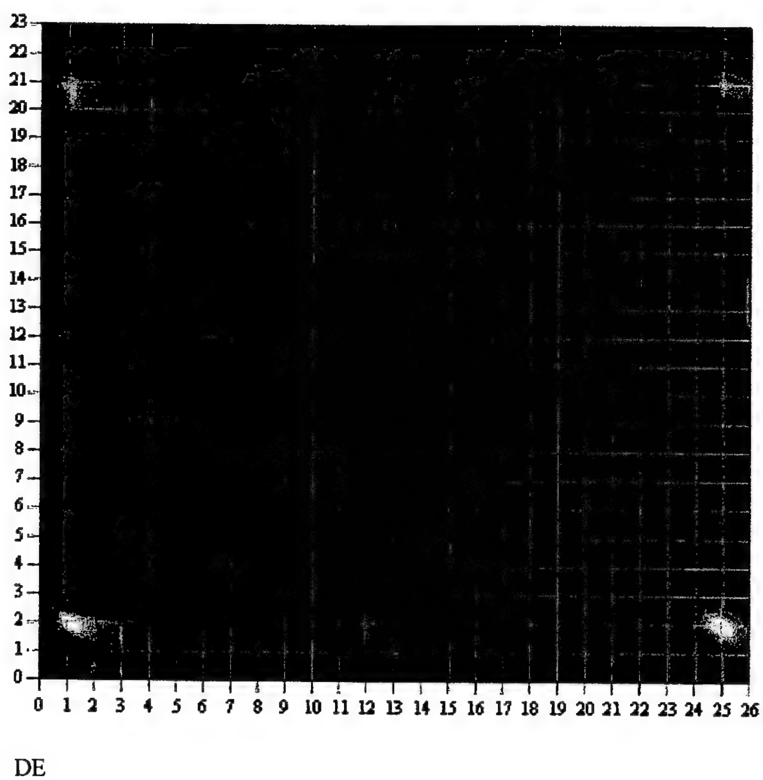

Figure 5. Enhanced Plot for Undamaged Foam Panel

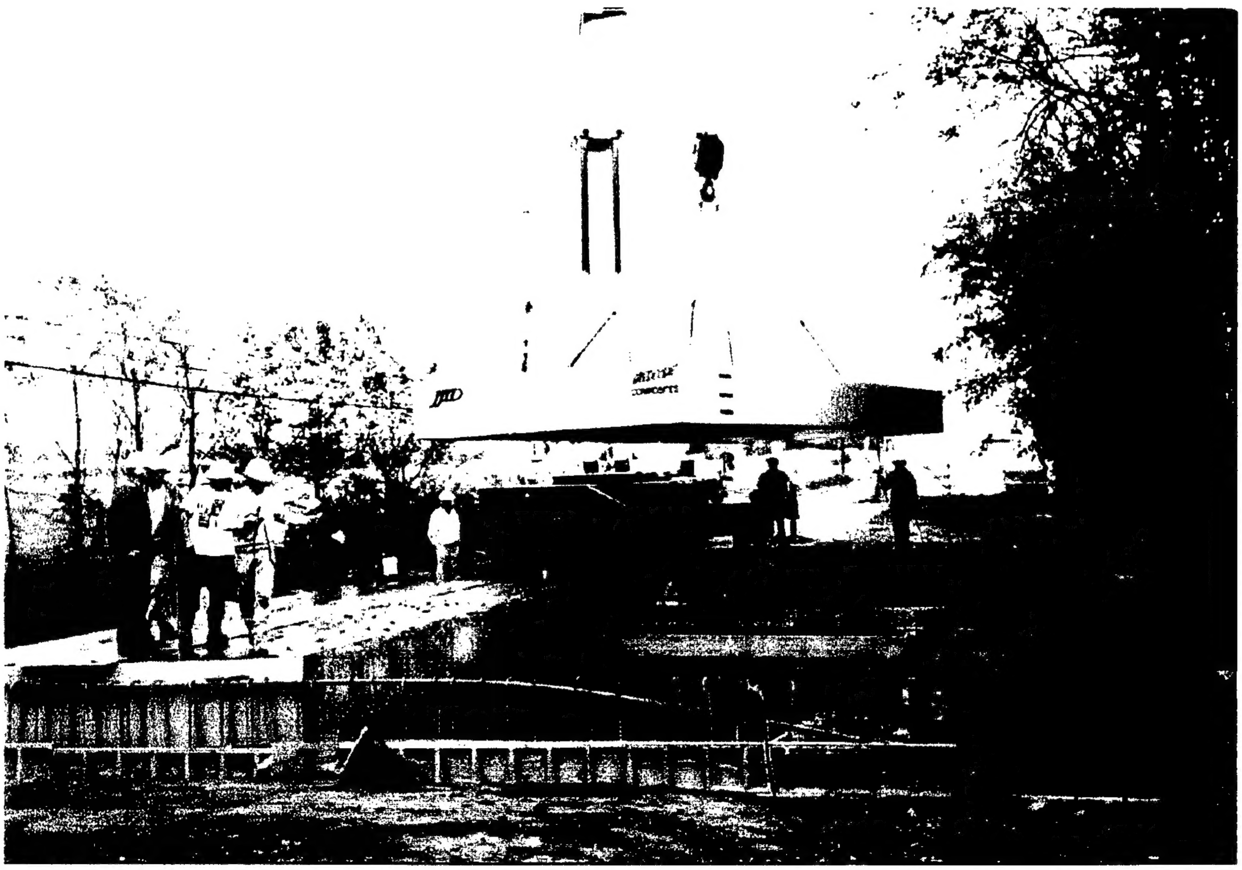

Figure 6. Installation of the All-FRP Bridge in Delaware

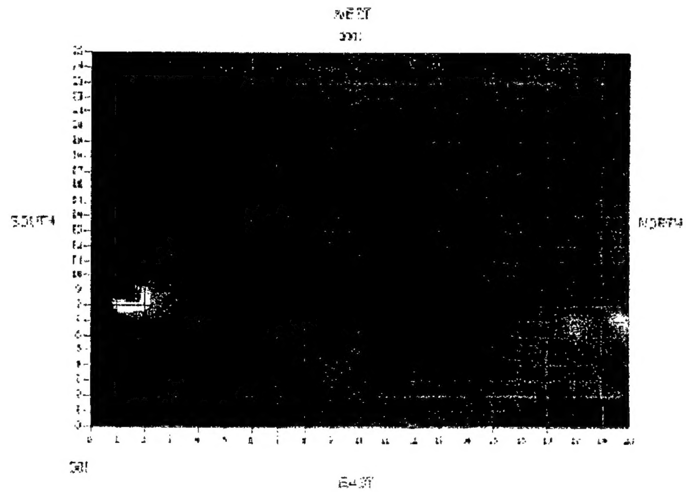

Figure 7. SIDER Summary Plot for the Delaware FRP Bridge (2001 Data)

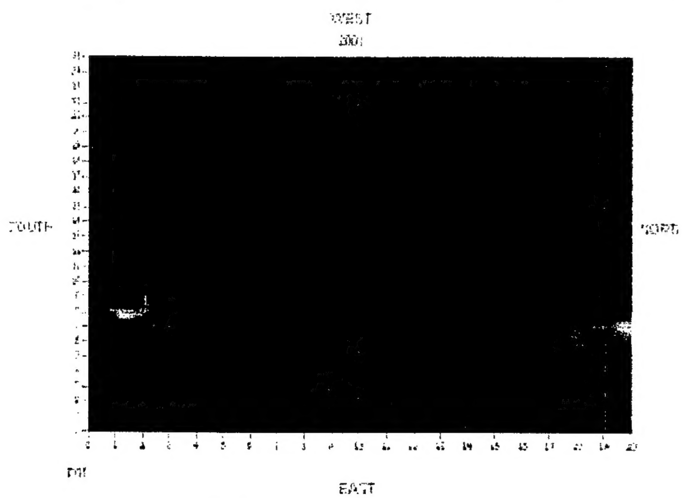

Figure 8. SIDER Enhanced Summary Plot for the Delaware FRP Bridge (2001 Data)

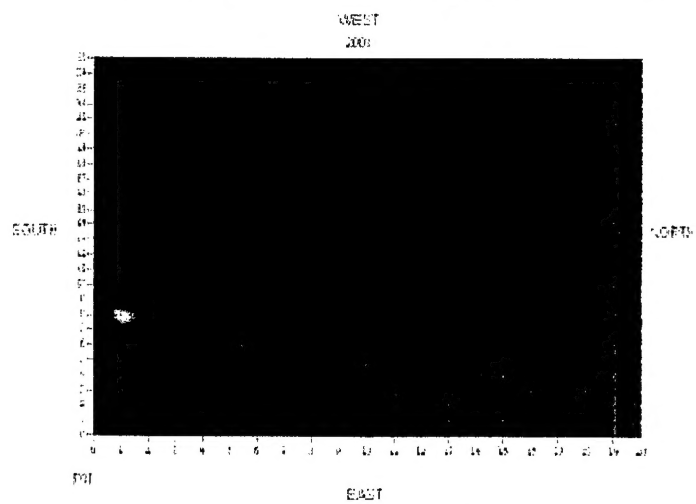

Figure 9. SIDER Rate Plot for the Delaware FRP Bridge (1999 - 2001)

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